REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 5/9/03	3. REPORT TYPE AND DATES COVERED Peer-reviewed reprint

4. TITLE AND SUBTITLE
Progress in Linear Optics Quantum Computing

5. FUNDING NUMBERS
DAAD19-02-1-0069

6. AUTHOR(S)
J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
43389.7-PH-QC

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Quantum logic operations can be performed using linear optical elements, ancilla photons, and corrections based on the results of measurements made on the ancilla. We have recently demonstrated several basic quantum logic operations using single photons, a technique for feed-forward control, a new source of single photons on pseudo-demand, and a quantum memory device for single photons.

14. SUBJECT TERMS
Quantum computing, ancilla, high-fidelity

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20030523 078

43389.7

PROGRESS IN LINEAR-OPTICS QUANTUM COMPUTING

J. D. FRANSON, M. M. DONEGAN, M. J. FITCH,
B. C. JACOBS, AND T. B. PITTMAN

Johns Hopkins University, Applied Physics Laboratory, Laurel, MD 20723, USA
E-mail: franson@jhuapl.edu

Quantum logic operations can be performed using linear optical elements, ancilla photons, and corrections based on the results of measurements made on the ancilla. We have recently demonstrated several basic quantum logic operations using single photons, a technique for feed-forward control, a new source of single photons on pseudo-demand, and a quantum memory device for single photons.

1 Introduction

Knill, Laflamme, and Milburn (KLM) recently showed[1] that quantum logic operations can be performed using linear optical elements, such as beam splitters and phase shifters. The input qubits, represented by single photons, are combined with additional photons (ancilla) using linear optical elements, after which measurements are made on the ancilla. In the original KLM approach, the output of a logic device is only accepted if the measurements yield specific results (post-selection), whereas the results are always accepted in an alternative approach that we recently suggested.[2] In either case, measurement-dependent corrections are applied to the output and the quantum-mechanical measurement process projects out a final state that corresponds to the desired logical output in the limit of a large number n of ancilla.

We have proposed[3] several quantum logic devices of this kind, including a quantum parity-check, quantum encoder, and a destructive controlled-NOT gate that performs the logical function of a conventional CNOT operation while destroying the control qubit in the process. These basic devices can be combined to implement a full (non-destructive) CNOT gate as described in Ref. 3. Our CNOT implementation makes use of polarization-encoded qubits,[4] which avoids the phase instabilities that can occur when using interferometers.

In the remainder of this paper, we will describe recent experimental demonstrations of a quantum parity-check and a destructive CNOT gate.[5] We have also implemented[6] the feed-forward techniques required to correct the output of the logic gates, along with a new source of single photons on pseudo-demand,[7] and a quantum memory device for single photons.[8] A "high-fidelity" approach[2] to linear-optics quantum computing will also be briefly discussed.

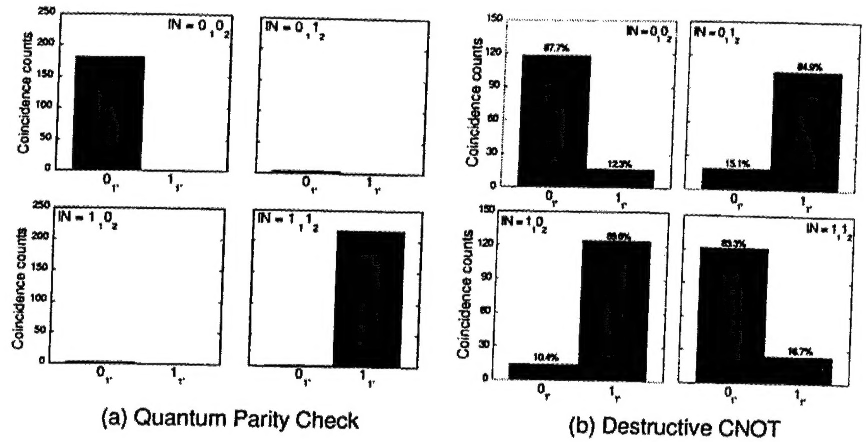

Figure 1. Results from (a) the quantum parity-check experiment, and (b) the destructive CNOT experiment.

2 Experiments

We have performed several proof-of-principle experiments in which a pair of photons was produced using parametric downconversion. The polarizations of the photons could be controlled using wave plates to form superpositions of input states to the logic devices to be tested. The outputs of the logic devices were measured using polarization analyzers and single-photon detectors. All of the current experiments were performed in the coincidence basis, in which the detection of the output photons was required in order to ensure the performance of the correct logic operation.

The results from an experimental demonstration[5] of the quantum parity-check are shown in Figure 1(a). The logical output of the device is shown for all of the possible values of the input qubits. The dark areas represent the correct logical output and the shaded areas represent errors. In this case the errors were on the order of 1%. Similar results were also obtained for superposition states of the input qubits, which shows that the device maintains the coherence of the output qubits.

Figure 1(b) shows the experimental results[5] from a destructive CNOT logic gate. The intended function of this device is to flip or invert the value of the target qubit if and only if the control qubit has the value 1. Once again, the dark areas represent the correct result and the shaded areas, which were on the order of 13% in this experiment, represent errors. Most of this error rate was due to mode mismatch, and we are in the process of repeating the experiment using single-mode fibers in an effort to reduce the error rate.

As mentioned above, real-time corrections must be made to the output

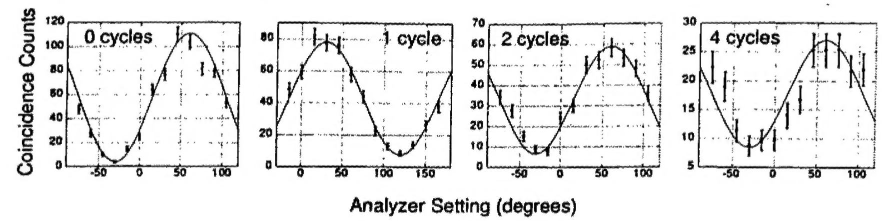

Figure 2. Input and output polarization states in the quantum memory experiment.

of the logic devices when certain results are obtained from the measurement made on the ancilla photons. We have applied these feed-forward correction to the output of the quantum parity check using a high-speed Pockels ce and a short length of optical fiber to delay the output while the electronic applied the required voltage to the cell.[6] The Pockels cell in this experimen had a rise time of approximately 10 ns, which was sufficient for a real-tim correction to the output.

Large numbers of single-photons will be required in a linear-optics ap proach to quantum computing. We have recently demonstrated[7] a new sourc of single photons that are available at periodic time intervals that can be syn chronized with the cycle time of a quantum computer, which we refer to as source of single photons on pseudo-demand. In this approach, the detection c one member of a downconverted pair of photons caused the second photon t be switched into an optical storage loop using a high-speed Pockels cell. Afte it was known that a single photon was present in the loop, it could be switche out of the storage loop when needed. The experimental results showed a los of approximately 17% per cycle time,[7] which we expect to reduce in the futur using low-loss switches.

A storage loop and high-speed switch can also be used to implemen a quantum memory device for single photons. Here the switch must no affect the state of polarization of the photonic qubit. We have performed proof-of-principle demonstration[8] of a memory device[9] of this kind in whic a Sagnac interferometer was used as the high-speed switching element. Th experimental results of Figure 2 show the polarization of the input qubit an that of the output after four cycles through the device. The performance of th memory device is also being improved using an optical fiber implementatio

3 High-fidelity quantum logic operations

The logic devices originally suggested by KLM[1] give the correct output aft post-selection with a failure probability that scales as $1/n$. We have recentl proposed[2] an alternative approach in which the output of the logic devices i

always accepted (no post-selection), while the entangled state of the ancilla photons is chosen to maximize the fidelity of the output. This results in an intrinsic error rate of $(1/n)^2$, which we expect to have practical advantages in quantum computing applications. In particular, our high-fidelity approach allows a specific error threshold to be met with a smaller number of ancilla photons than in the original KLM approach, assuming that the error correction code must be able to correct for the most general errors. Reducing the number of ancilla photons will reduce the probability of an error in the generation of the ancilla photons, which in turn will make it easier to achieve the error threshold.

4 Summary

We have performed proof-of-principle demonstrations of basic quantum logic operations using single photons, feed-forward control techniques, a new source of single photons on pseudo-demand, and a quantum memory device for single photons. All of these devices have errors on the order of 15% per operation and their performance would have to be greatly improved for any practical applications. Nevertheless, these results represent a first step towards the long-term goal of linear-optics quantum computing.

Acknowledgments

This work was funded by ONR, ARO, NSA, ARDA, and IR&D funds.

References

1. E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001).
2. J. D. Franson, M. M. Donegan, M. J. Fitch, B. C. Jacobs, and T. B. Pittman, Phys. Rev. Lett. **89**, 137901 (2002).
3. T. B. Pittman, B. C. Jacobs, and J. D. Franson, Phys. Rev. A **64**, 062311 (2001).
4. M. Koashi, T. Yamamoto, and N. Imoto, Phys. Rev. A. **63**, 030301 (2001).
5. T. B. Pittman, B. C. Jacobs, and J. D. Franson, Phys. Rev. Lett. **88**, 257902 (2002).
6. T. B. Pittman, B. C. Jacobs, and J. D. Franson, to appear in Phys. Rev. A (2002); quant-ph/0204142.
7. T. B. Pittman, B. C. Jacobs, and J. D. Franson, to appear in Phys. Rev. A (2002); quant-ph/0205103.
8. T. B. Pittman and J. D. Franson, submitted to Phys. Rev. A (2002); quant-ph/0207041.
9. S. Lloyd, M. S. Shahriar, J. H. Shapiro, and P. R. Hemmer, Phys. Rev. Lett. **87**, 167903 (2001).